

9-28-2017

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## Recommended Citation

Tasolamprou, Anna C.; Koschny, Thomas; Kafesaki, Maria; and Soukoulis, Costas M., "Near-Infrared and Optical Beam Steering and Frequency Splitting in Air-Holes-in-Silicon Inverse Photonic Crystals" (2017). *Ames Laboratory Accepted Manuscripts*. 49.  
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## **Abstract**

We present the design of a dielectric inverse photonic crystal structure that couples line-defect waveguide propagating modes into highly directional beams of controllable directionality. The structure utilizes a triangular lattice made of air holes drilled in an infinitely thick Si slab, and it is designed for operation in the near-infrared and optical regime. The structure operation is based on the excitation and manipulation of dark dielectric surface states, in particular on the tailoring of the dark states' coupling to outgoing radiation. This coupling is achieved with the use of properly designed external corrugations. The structure adapts and matches modes that travel through the photonic crystal and the free space. Moreover it facilitates the steering of the outgoing waves, is found to generate well-defined, spatially and spectrally isolated beams, and may serve as a frequency splitting component designed for operation in the near-infrared regime and in particular the telecom optical wavelength band. The design complies with the state-of-the-art Si nanofabrication technology and can be directly scaled for operation in the optical regime.

## **Keywords**

photonic crystals, dielectric media, surface states, directional emission, frequency splitting, beam steering

## **Disciplines**

Atomic, Molecular and Optical Physics | Physical Chemistry

# Near infrared and optical beam steering and frequency splitting in air holes-in-silicon inverse photonic crystals

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## Abstract

We present the design of a dielectric inverse photonic crystal structure that couples line-defect waveguide propagating modes into highly directional beams of controllable directionality. The structure utilizes a triangular lattice made of air holes drilled in an infinitely thick Si slab and it is designed for operation in the near infrared and optical regime. The structure operation is based on the excitation and manipulation of dark dielectric surface states, in particular on the tailoring of the dark states coupling to outgoing radiation. This coupling is achieved with the use of properly designed

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external corrugations. The structure adapts and matches modes that travel through the photonic crystal and the free space. Moreover it facilitates the steering of the outgoing waves, it is found to generate well defined, spatially and spectrally isolated beams and may serve as a frequency splitting component designed for operation in the near infrared regime and in particular the telecom optical wavelength band. The design complies with the state-of-the-art Si nano-fabrication technology and can be directly scaled for operation in the optical regime.

## Keywords

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Dielectric photonic crystals are the electromagnetic wave analogue of electronic semiconductors. They consist of periodically alternating regions of different dielectric materials that allow the modification of the electromagnetic wave dispersion properties.<sup>1-4</sup> Photonic crystals structures are theoretically infinite structures; however, when it comes to actual implementations, their size is in fact finite. The finite size gives rise to various additional phenomena that depend on the interfaces of the photonic crystal regions and the surrounding environment. One of the phenomena related to the finite size is the appearance of surface states, also known as surface modes, see e.g. Ref.,<sup>5</sup> that propagate bound to the interface of the dielectric photonic crystals and the external space, similarly to the surface plasmon polaritons found at the metal-dielectric interfaces at high frequencies.<sup>5-8</sup> For many years, photonic crystals surface states have been generally treated as a subsidiary effect. Surface states on photonic crystals are dark states, meaning that they cannot couple directly to free-space propagating waves because the surface wave vector cannot be matched. In the past decade a surface plasmon polariton related experiment revealed an interesting potential for exploiting these dark states. In particular it has been demonstrated that surface plasmon polaritons can be used to enhance and control the collimation and directionality

of the electromagnetic energy that exits a subwavelength metallic slit surrounded by side corrugations.<sup>9–13</sup> The work on the metallic slits inspired a series of investigations into the manipulation of the dielectric photonic crystal surface states and their role in shaping the electromagnetic energy that comes out from a dielectric photonic crystal-based structure. As a result, it has been found that the termination of the photonic crystal structure can be designed to provide desired surface wave dispersion properties,<sup>14–17</sup> while an additional corrugation can undertake the coupling of the dark surface states to outgoing radiation. The mechanism has been employed, amongst else, to sustain the collimation of free-space travelling beams,<sup>18,19</sup> to produce and control near field focusing effects<sup>20,21</sup> and to decrease the  $\pi$  angular spread, or  $2\pi$  for solid angle in 3D, of a forward propagating beam that exits a subwavelength photonic crystal waveguide operating in the microwave and optical regime.<sup>22–26</sup> Moreover, in the case on the microwave regime and the corresponding high dielectric rods in air photonic crystals, it has been shown both theoretically and experimentally that the angle of the beams directionality can be tuned by properly designing the terminating corrugations.<sup>27,28</sup> The frequency dependent bend of the beams provides steering and frequency splitting capabilities and consequently the manipulation of the dielectric, ohmic loss-free, surface waves may be used in a variety of applications involving free space coupling, as for example in de-multiplexer components for optical communications, optical spectroscopy and sensor applications, etc.<sup>29–32</sup>

In this work we present the design of a dielectric photonic crystal-based frequency splitting and beam steering component for operation in the near infrared regime and in particular the telecom optical band, ranging from 1260 nm to 1625 nm. Employing air-holes-in bulk dielectric design rather than the most forward dielectric-rods-in-air approach enables the fabrication of photonic structures that can be more easily scaled to infrared and optical wavelengths. Si-based, ohmic loss-free, frequency splitting components operating in these short wavelengths are of high interest for application in optical nano-circuitry. Recent works have demonstrated the development of silicon waveguide-based de-multiplexers,<sup>33</sup> all-dielectric

multi-layered ring structures for beam collimation and steering,<sup>34</sup> all-dielectric asymmetric dimers for tunable directional scattering.<sup>35</sup> In a similar way, our structure provides control over the direction of the energy that comes out from optical components made of dielectric air holes-in-Si photonic crystals which, to our knowledge, has not been demonstrated yet. The advantage of using photonic crystals for controlling the free-space outgoing beams is that, apart from achieving the aforementioned operations, it enables the communication between the mature Si-based photonic crystal optical circuits and the outside world in a natural manner.

Our component consists of a line-defect waveguide that feeds the bulk photonic crystal termination which is properly designed to sustain surface modes. Additional, properly aligned, scatterers are used to couple the dark surface waves to radiation modes. We have already validated experimentally the principle of operation for the dielectric-rods-in-air complementary structure in the microwave regime.<sup>28</sup> However, due to fabrication constraints, this geometry is ill suited for applications in the near infrared and optical regime. In order to scale the structure down for operation in shorter wavelengths a photonic crystal geometry consisting of air holes in a bulk dielectric material is a better candidate for fabrication. We also take into account the available materials and the current fabrication feasibility in the near infrared and optical regime. For the existence of well defined, wide bandgaps the materials involved should exhibit high refractive index contrast (one of the materials is air). Materials such as  $\text{TiO}_2$ , GaAs,  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  or Si exhibit sufficiently high permittivity at the infrared and optical regime and at the same time they have practically no losses below their band edges.<sup>36-39</sup> As far as the fabrication of the components at these wavelengths is concerned, CMOS compatible methods, such as ion beam etching, allow the creation of void air pores in Si and the creation of inverse photonic crystals with lattice constants in the order of some hundreds of nanometers.<sup>40-42</sup> Consequently, we choose to investigate a two dimensional structure (of infinite thickness) which is considered to be made of a Si slab perforated with air holes in a triangular arrangement and provides directionality control in the

horizontal plane. In the second subsection we present the details of the structure and dispersion properties of its surface states. In third subsection we present the evaluation of the structure as a beam steering and frequency splitting component in the infrared regime. The component can be directly scaled down for operation in the optical regime. Moreover the present design could be used as a preliminary investigation for the extension to the widely investigated three dimensional Si based inverse woodpiles<sup>43,44</sup> with the possibility of beam shaping and directionality control in both the horizontal and vertical plane.

## Dielectric dark state manipulation

We present the design of an air holes-in-Si inverse photonic crystal-based structure that controls the directionality of the energy coming out from a line-defect photonic crystal waveguide. The operation is based on the excitation and manipulation of dark, surface propagation modes. The structural element of our steering component is the bulk, dielectric photonic crystal schematically shown in Fig. 1a. It consists on an infinitely thick silicon slab where circular air holes are drilled in a two-dimensional standard triangular lattice arrangement. The lattice constant is equal to  $\alpha = 320$  nm and the diameter of the air cylinders (holes) is equal to  $D = 188$  nm; the permittivity of the silicon is equal to  $\varepsilon = 11.6$ . We choose to use the triangular lattice arrangement and TM polarization with the principal field component  $\mathbf{H} = H_z$ . TM polarization is proven to provide wider bandgaps in such photonic crystal structures.<sup>45</sup> The photonic crystal exhibits a full photonic band gap within the range  $\alpha/\lambda = [0.183, 0.276]$  or  $\lambda = [1.15 \mu\text{m}, 1.74 \mu\text{m}]$ , that is the bandgap spans the range of the optical telecommunications band. The photonic band gap is marked with the yellow area in Fig. 1c.

Photonic crystals have been proven to allow the propagation of surface states provided that they are properly terminated. To this end the surface termination must break the lateral symmetry of the bulk periodic structure. Each termination provides different characteristics for the surface mode and it is essentially a design element that controls the dispersion and

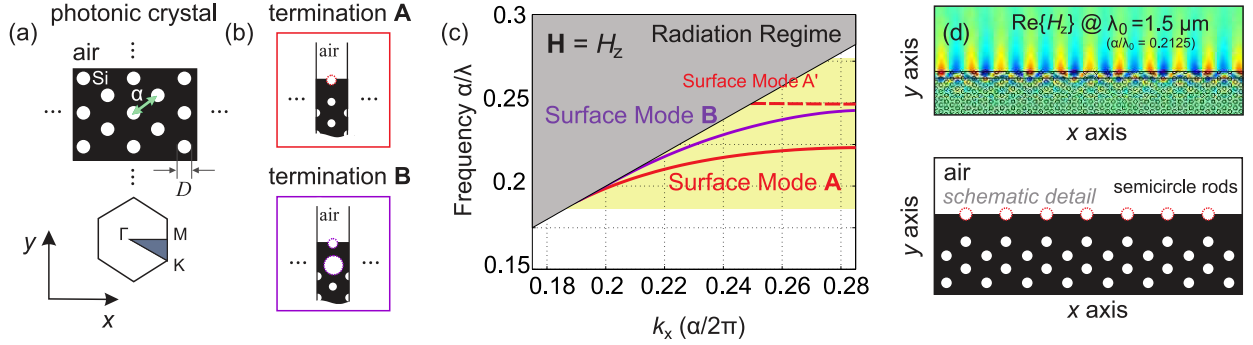


Figure 1: (a) Schematic of the infinite two-dimensional photonic crystal which is the basic structural element of the photonic component discussed here. It consists of circular air rods of diameter  $D = 188$  nm drilled in an infinite silicon slab with permittivity  $\varepsilon = 11.6$ . The photonic crystal arrangement is triangular and the lattice constant is  $\alpha = 320$  nm. (b) Schematic of the supercells termination used for sustaining the surface modes, **A** (red frame) and **B** (purple frame). (c) Dispersion diagram of the supported surface modes for terminations **A** (red curves) and **B** (purple curve). The polarization is  $\mathbf{H} = H_z$ . Red solid line corresponds to the acoustic surface mode for the termination **A** and red dashed line corresponds to the optical, nearly flat surface mode for the termination **A**. Purple solid line corresponds to the sole surface mode supported by the termination **B**. The shaded yellow area corresponds to the photonic bandgap of the structure. (d) Field distribution of the real part of the  $H_z$  component of the field in an infinitely wide (along  $x$ ) photonic crystal with termination **A**, at  $\lambda_0 = 1.5\mu\text{m}$ , ( $\alpha/\lambda_0 = 0.2125$ ), and corresponding structure schematic.



the field distribution of the surface states. For the present design we choose to use two types of surface termination, termination **A** and termination **B**, that are schematically shown in Fig. 1b. In both configurations we choose initially to omit the second row of the cylindrical air element and horizontally etch the whole structure at the middle of the external rods, creating in this way semicircles as seen schematically in Fig. 1b. We select the specific surface termination aiming both at facilitating an actual fabrication of the component and ensuring the efficiency of the desired electromagnetic operation. In that sense the second omitted row allows space for the implementation of additional rods necessary for the coupling of the dielectric dark surface states to outgoing radiation modes. At the same time it allows space for varying the diameter of the underlying rods as it happens for termination **A** and **B**. In particular the diameter is equal to  $D_A = D = 150$  nm for case **A** and  $D_B = 300$  nm for case **B**. By modifying the diameters of the rods, the filling ratio, air:silicon area, changes and so does the dispersion of the surface mode. This control over the surfaces states is useful for achieving oblique beaming operation. Finally the semicircle cropped rods increase the wavelength range the surface modes and further facilitate the coupling to the outgoing radiation.

The dispersion diagrams of the supported surface states for termination **A** and **B** are presented in Fig. 1c. They are calculated by solving the eigenvalue problem in a supercell with sufficiently large areas of surrounding air while imposing floquet periodic conditions at the external boundaries. Surface states lie within the photonic band gap, which is marked with the yellow area, and below the light line. Red curves correspond to surface modes of termination type **A**. Red solid line corresponds to the low frequency, acoustic, surface mode and the red dashed line corresponds to the high frequency, optical, surface mode. The red solid branch is referred to as acoustic because it initiates from zeroing at the  $k_x = 0$  edge of the Brillouin zone. In contrast, the optical modes of the red dashed branch are characterized by non-zero frequency at  $k_x = 0$ . The low frequency surface state is pushed up by the dielectric band and the optical surface state is pulled down from the air band. The high

frequency surface state is characterized by a small negative band slope (nearly flat) which translates in backward propagating waves;<sup>46</sup> it is well spectrally separated from the acoustic surface state and therefore we will not take it in to account in the design. The acoustic surface mode **A** expands in a wavelength range of  $\Delta\lambda = 220$  nm around the wavelength  $\lambda = 1.52 \mu\text{m}$  ( $\alpha/\lambda_0 = 0.21$ ). The surface mode (acoustic) for the termination **B** is shown in purple. It is the single supported surface state for termination **B**. The diameter of the underlying rods in termination **B** is increased with respect to case **A** (schematic in Fig. 1b). As the air:silicon ratio of the second row in termination **B** increases, the surface mode is pushed to higher frequencies approaching the light line. This is verified in Fig. 1c where we see that surface mode **B** expands in a wavelength range of  $\Delta\lambda = 310$  nm around the wavelength  $\lambda = 1.46 \mu\text{m}$  ( $\alpha/\lambda_0 = 0.219$ ). It is also noted here that neither the surface mode **B** overlaps with the optical surface mode **A**. Finally, the distribution of the real part of the  $H_z$  component for the acoustic surface mode of termination **A** in a horizontally infinite structure, at wavelength  $\lambda_0 = 1.5\mu\text{m}$  ( $\alpha/\lambda_0 = 0.2125$ ), is presented in Fig. 1d. It is observed that the surface wave stands bound to the interface of the two semi-infinite domains, that is, the photonic crystal and the air, and it decays exponentially in both domains away from the interface.

## **Coupling from line-defect waveguide modes to oblique directional beams; frequency splitting operation**

One important motivation to invest on the manipulation of surface states is establishing a means of communication between the electromagnetic waves that travel through the dielectric photonic crystal circuits and the outside world. Having designed the surface termination, we proceed by investigating the interaction between the terminating interface and a simple, straight line-defect waveguide. The line-defect waveguide is created by omitting an entire row/rows of air rods which leads to the formation of a high index slab surrounded by the reflective inverse photonic crystal. It is schematically shown in the inset of Fig. 2. The width

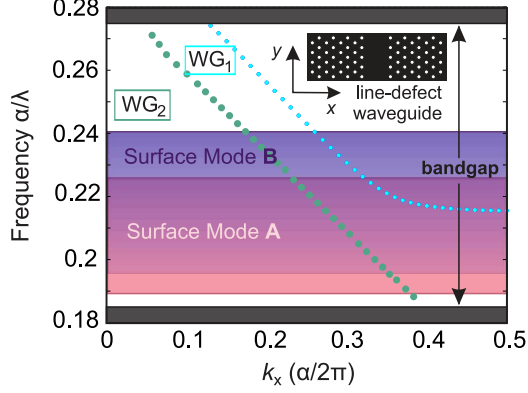


Figure 2: Dispersion diagram of the fundamental mode for the line-defect waveguide that feeds the surface mode, the schematic is shown in the inset. Light blue curve corresponds to the case of the waveguide of one rod width,  $WG_1$ , and the green curve corresponds to the case of five rod width,  $WG_2$ . Grey shaded areas delimit the photonic bandgap of the infinite photonic crystal. The pink shaded area corresponds to the surface mode **A** frequency regime and the purple shaded area corresponds to surface mode **B**. The dispersion of the corresponding surface states along  $k_x$  is shown in Fig. 1c.

of the waveguide corresponds to the number of the omitted rods and affects the characteristics of the propagating guided modes.

Figure 2 presents the dispersion diagram of the fundamental propagating modes for two line-defect waveguides of different width. Waveguide  $WG_1$  corresponds to a line-defect of one omitted air rod and  $WG_2$  to a waveguide of five omitted air rods. The propagating guided modes lie within the photonic bandgap which is delimited by the grey shaded areas in Fig. 2. Apart from the photonic bandgap in Fig. 2 we also mark the surface states spectrum. In particular, the wavelength regime of the surfaces mode is marked with the pink and the purple shaded area. The values are derived by the band diagrams of Fig. 1c for modes **A** and **B** respectively. We specifically mark this area as for the coupling of the line-defect modes and the surface states we primarily need spectral overlap. As it is observed in Fig. 2, the fundamental mode of  $WG_1$  waveguide does not extent to the whole spectrum of the bandgap and its spectral overlap with the surface modes is significantly small. This prohibits the use of  $WG_1$  waveguide for feeding the surface modes in a wide range of wavelengths. The spectral extend of the fundamental mode for the five rod width waveguide,  $WG_2$ , appears to serve

our purpose better. In particular the fundamental mode of  $WG_2$ , which is plotted with the green line in Fig. 2, is very broadband (extends to the whole bandgap) and exhibits a 100% overlap with the surface modes. Thus using the five rod width line-defect waveguide,  $WG_2$ , and the excitation with the fundamental mode is considered the optimum configuration for achieving surface states excitation and directional coupling operation.

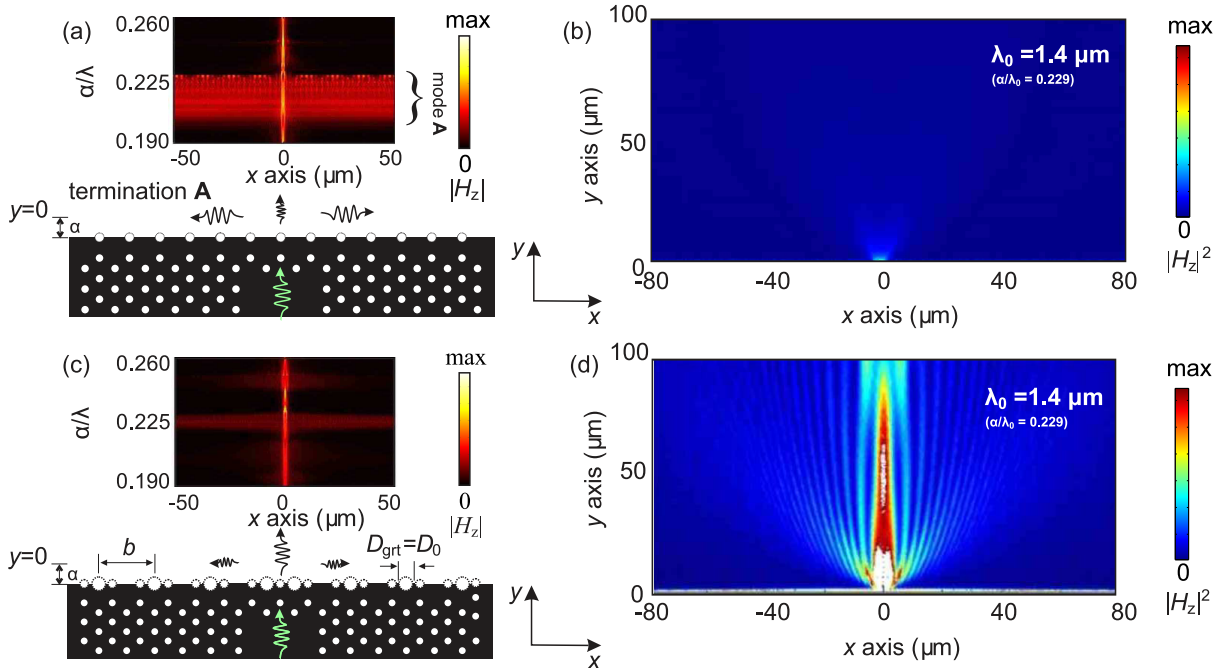


Figure 3: Line  $x$ -cross-section profile of the field intensity in the near field, that is at the exit of the terminating interface, within the range of  $\alpha/\lambda = [0.195, 0.265]$  for the case of (a) surface termination of type **A** without additional scatterers and (c) surface termination of type **A** with additional scatterers. Corresponding schematics are also shown. Snapshots of the spatial energy distribution of the forward propagating wave for the case of (b) surface termination of type **A** without additional scatterers and (b) surface termination of type **A** with additional scatterers. The wavelength of the operation is equal to  $\lambda_0 = 1.4 \mu\text{m}$  ( $\alpha/\lambda = 0.229$ ).

The  $WG_2$  line-defect waveguide along with the terminating interface (termination of type **A**) is shown in the schematic of Fig. 3a. The fundamental waveguide mode is exited at the input port and the wave travels in the  $\Gamma K$  ( $k_x = 0$ ,  $k_y \neq 0$ ) direction towards the photonic crystal/air interface. At this point the waveguide energy is scattered generating waves with

non-zero  $k_x$  components that are partially coupled to the surface waves propagating in  $\Gamma\text{M}$  ( $k_x \neq 0, k_y = 0$ ) direction and partially converted into a free space spherical wave leaking from the waveguide effective aperture. That is, the coupling is a result of the waveguide and the termination intersection that breaks both the vertical and lateral symmetry. The final goal is the generation of well-defined outgoing beam from the surface mode and it is achieved by increasing the effective width of the grating and by minimizing the waveguide aperture leakage versus the surface mode. In order to enhance the energy transfer from the waveguide mode to the surface waves we introduce an intermediate coupling element. The intermediate coupling element lies inside the waveguide and close to the terminating area. It consists of five additional scatterers that intervene between the surface termination and the line defect waveguide; one row of two holes and one row of three holes. This region acts as an impedance matching element between the waveguide and the termination. It has been found to increase the surface propagating energy with respect to the forward leakage but, at the same time, it also increases the return losses in the feeding waveguide. This consequently leads to the deterioration of the overall coupling efficiency. In fact, in the present designs the return losses are on average as high as 60%. Evidently there is interplay between the coupling losses and the quality of the outgoing beams. Given that the focus is at the later we consider that the increase of the overall coupling losses is a fair trade-off for the quality of the beams. Further optimization may be possible.

We investigate initially, the excitation of the surface states in the structure with solely termination of type **A**, that is without any additional grating scatterers. In particular we record the  $x$ -cross-section profile of the field intensity in the the near field within a wavelength range of  $\alpha/\lambda = [0.19, 0.26]$ . The results are presented in Fig. 3a. The profiles are calculated at the exit of the terminating interface, that is at  $y = 0$  (which corresponds to a distance of  $\alpha$  from the termination) and extends in the range  $[-50\mu\text{m}, 50\mu\text{m}]$  along the  $x$  axis. As seen in Fig. 3a, in the wavelength range where the surface mode is excited, the energy spreads along the photonic crystal-air interface and less energy goes to the forward

direction. Figure 3b shows a snapshot of the energy distribution of the wave that exits the structure at the wavelength of  $\lambda_0 = 1.4 \mu\text{m}$  ( $\alpha/\lambda = 0.229$ ). The absence of a collimated beam is verified. The next step is to add, symmetrically in both exit sides, the additional scatterers as it is shown in the schematic of Fig. 3c. The additional scatterers, also referred to as grating modulation, facilitate the coupling of the dark surface states into outgoing radiation. In particular, the interaction of the surface wave and the scatterer generates diffracted waves with non-zero wave vector components that interfere constructively in the forward direction.<sup>23</sup> The shape and the periodicity of the grating modulation is designed with respect to the fabrication feasibility. Thus each scatterer is a semi-circle air hole of diameter  $D_{grt} = D_0 = 340\text{nm}$  arranged in periodicity  $b = 2\alpha\sqrt{3}$ . The value of the periodicity provides the sufficient momentum for the surface wave to couple to radiation (the surface wave-diffraction equation should assume real solutions<sup>28,47</sup>). For the grating modulated structure we calculate the  $x$ -cross-section profile of the near field intensity in the range  $\lambda = [1.23, 1.68]$  ( $\alpha/\lambda = [0.19, 0.26]$ ), seen in Fig. 3c. Contrary to Fig. 3a, we now observe that the intensity of the surface wave decreases while the intensity of the field at the center exit of the structure is enhanced. Figure 3d presents the snapshot of the energy distribution of the exiting wave at the wavelength of  $\lambda_0 = 1.4 \mu\text{m}$  ( $\alpha/\lambda = 0.229$ ). In this case the sideways propagating surface wave interacts with the periodic scatterers and undergoes successive diffractions. This leads to the formation of the narrow high directional beam in the forward direction. In summary, Fig. 3 describes the way that the spread of the beam that exits the line-defect waveguide depends on the surface termination.

In the case of Fig. 3 the symmetry of the surface termination and the grating with respect to the waveguide leads to beam emission along the forward direction, the  $y$ -axis. Off-axis directional emission can be achieved when one breaks this symmetry. In Ref.<sup>28</sup> we have demonstrated experimentally a dielectric rod photonic crystal configuration that provides off-axis emission and frequency splitting operation in the microwave regime. Given the fabrication restrictions in the present air holes-in-Si inverse photonic crystal structure,

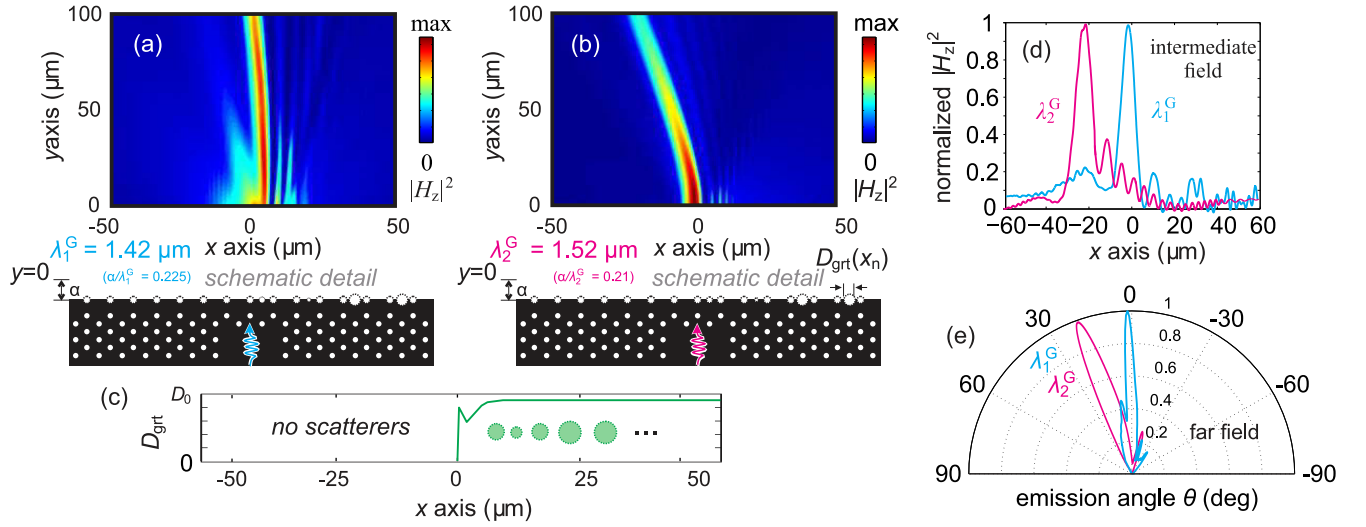


Figure 4: Case of a single-sided grating modulation: (a) Energy distribution of the outgoing field in the near and intermediate field region at  $\lambda_1^G = 1.42 \mu\text{m}$  ( $\alpha/\lambda_1^G = 0.225$ ) and schematic detail of the structure. (b) Energy distribution of the outgoing field in the near and intermediate field region at  $\lambda_2^G = 1.52 \mu\text{m}$  ( $\alpha/\lambda_2^G = 0.21$ ) and schematic detail of the structure. (c) Scatterer diameter modulation  $D_{\text{grt}}$  along the  $x$  axis. (d) Comparison of the beam spatial distribution in the near and intermediate field region at wavelength  $\lambda_1^G = 1.42 \mu\text{m}$  ( $\alpha/\lambda_1^G = 0.225$ ) and  $\lambda_2^G = 1.52 \mu\text{m}$  ( $\alpha/\lambda_2^G = 0.21$ ). (e) Comparison of the beam spatial distribution in the far field region at wavelength  $\lambda_1^G = 1.42 \mu\text{m}$  ( $\alpha/\lambda_1^G = 0.225$ ) and  $\lambda_2^G = 1.52 \mu\text{m}$  ( $\alpha/\lambda_2^G = 0.21$ ).

we choose to follow two alternative paths to achieve beam steering and frequency splitting for the infrared and optical regime. The first oblique beaming implementation is presented in the schematic of Fig. 4a and 4b. It consists of the line-defect waveguide, the intermediate coupling element and an asymmetric grating layer. In particular only one exit side (right) hosts scatterers while the other side contains only the surface termination of type **A**. In this design, the absence of grating scatterers on one side of the termination leads to non-directional leakage from the surface propagating wave and is expected to further increase the overall coupling losses. To reduce the impedance mismatch and optimize the quality of the outgoing beams the diameter of the grating scatterers is variable along the  $x$  axis. The optimized function of the scatterers diameter  $D_{grt} = D_{grt}(x_n)$ , where  $x_n = nb$  and  $n = [0 \dots 50]$ , is presented in Fig. 4c. Figure 4a presents the spatial distribution of the energy emerging from the structure at the wavelength  $\lambda_1^G = 1.42 \mu\text{m}$  ( $\alpha/\lambda_1^G = 0.225$ ). A well defined beam at an angle of  $\theta_1^G = +1$  deg from the forward direction is observed. Close to the exit of the structure, in the near field regime, we observe the existence of side lobes (to the right) and an unshaped scattered lobe (to left) that does not propagate significantly to the intermediate field and far field (seen in Fig. 4e). Figure 4b presents the spatial distribution of the energy emerging from the structure at the wavelength  $\lambda_2^G = 1.52 \mu\text{m}$  ( $\alpha/\lambda_2^G = 0.21$ ). A well defined beam at an angle of  $\theta_2^G = +23$  deg from the forward direction is observed. Here, the side lobes are suppressed. Figure 4d presents the comparison of the spatial distribution of the outgoing energy in a  $x$ -cross section of the intermediate field regime ( $y = 100\mu\text{m}$ ). Blue curve corresponds to the  $\lambda_1^G = 1.42 \mu\text{m}$  ( $\alpha/\lambda_1^G = 0.225$ ) directional emission (Fig. 4a) and magenta curve corresponds to the  $\lambda_2^G = 1.52 \mu\text{m}$  ( $\alpha/\lambda_2^G = 0.21$ ) directional emission (Fig. 4b). The beams are well defined and exhibit low spatial overlap. The comparison of the far field radiation for the two wavelengths is presented in Fig. 4e. The far field radiation is well defined and the two beams exhibit angular separation of  $\Delta\theta^G = 22$  deg and spectral separation of  $\Delta\lambda^G = 100$  nm.

An alternative way to achieve oblique directionality of the outgoing beam in this photonic



crystal component is by implementing the structure presented in the schematics of Fig. 5a and Fig. 5b. It consists of the line-defect waveguide, the intermediate coupling component, an asymmetric surface termination of type **A** and **B** and a symmetric (both sides) grating configuration. Again, to reduce the impedance mismatch and optimize the quality of the outgoing beams the diameter of the grating scatterers is modulated along the  $x$  axis as seen in Fig. 5c. The asymmetric surface corrugation supports the propagation of surface modes with different dispersion as can be derived by the diagrams of Fig. 1c. At a certain wavelength the ratio  $k_x/k_0$  is different for termination **A** and **B**,<sup>47</sup> in Fig. 1c curves with red and purple respectively, and each side is expected to generate constructive interference in different directions for each particular wavelength. The spatial distribution of the energy emerging from the structure at wavelengths  $\lambda_1^S = 1.37 \mu\text{m}$  ( $\alpha/\lambda_1^S = 0.233$ ) and  $\lambda_2^S = 1.5 \mu\text{m}$  ( $\alpha/\lambda_2^S = 0.2125$ ) is presented in Fig. 5a and 5b respectively. In both cases we observe well defined emerging beams at angles  $\theta_1^S = +20 \text{ deg}$  and  $\theta_2^S = -23 \text{ deg}$  from the forward direction. The comparison of the  $x$ -cross section spatial distribution of the outgoing energy in the intermediate field regime ( $y = 100\mu\text{m}$ ) is presented in Fig. 5d. The two beams are well spatially separated, with angular separation  $\Delta\theta^S = 43 \text{ deg}$ , while their spectral separation is  $\Delta\lambda^S = 130 \text{ nm}$ . The far field radiation patterns for the two wavelengths are presented in Fig. 5e where we observe two well defined and separated beams. Compared to the previous implementation, presented in Fig. 4, we observe that the performance of the asymmetric surface termination implementation, presented in Fig. 5, slightly deteriorates. In particular the side lobes of the emerging beams presented in Fig. 5d and 5e are enhanced which is a result of the strong grating scattering and the increased impedance mismatch between the various elements of the components. Nevertheless, for the two wavelengths of the optical telecommunications band, the beams exhibit sufficiently enhanced spatial and spectral separation.

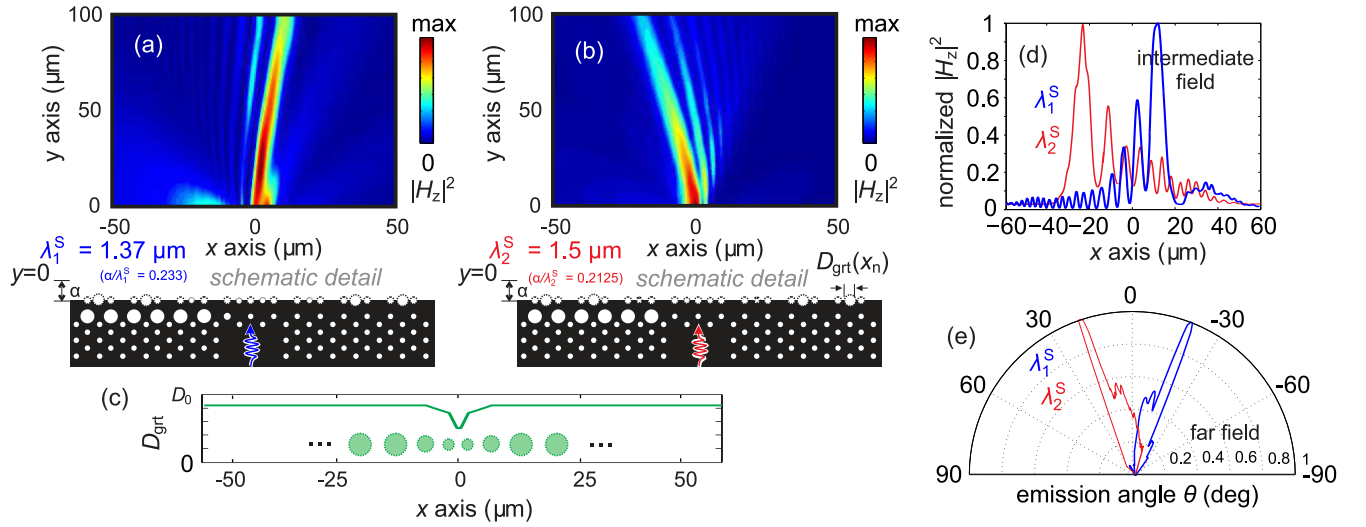


Figure 5: Case of an asymmetric surface termination: (a) Energy distribution of the outgoing field in the near and intermediate field region at  $\lambda_1^S = 1.37 \mu\text{m}$  ( $\alpha/\lambda_1^S = 0.233$ ) and schematic detail of the structure. (b) Energy distribution of the outgoing field in the near and intermediate field region at  $\lambda_2^S = 1.5 \mu\text{m}$  ( $\alpha/\lambda_2^S = 0.2125$ ) and schematic detail of the structure. (c) Scatterer diameter modulation  $D_{grt}$  along the  $x$  axis. (d) Comparison of the beam spatial distribution in the near and intermediate field region at wavelength  $\lambda_1^S = 1.37 \mu\text{m}$  ( $\alpha/\lambda_1^S = 0.233$ ) and  $\lambda_2^S = 1.5 \mu\text{m}$  ( $\alpha/\lambda_2^S = 0.2125$ ). (e) Comparison of the beam spatial distribution far field region at wavelengths  $\lambda_1^S = 1.37 \mu\text{m}$  ( $\alpha/\lambda_1^S = 0.233$ ) and  $\lambda_2^S = 1.5 \mu\text{m}$  ( $\alpha/\lambda_2^S = 0.2125$ ).

## Conclusions

We have presented a frequency splitting dielectric structure designed for operation in the near infrared, telecom optical band and optical regime. The structure is based on dielectric air holes-in-Si inverse photonic crystals made of an electromagnetically infinitely thick Si slab perforated with air holes in a standard triangular arrangement. It consists of a line-defect waveguide that feeds a surface termination designed to sustain the propagation of dark, surface states. Additional surface modulation grating provides the coupling of the surface states to outgoing radiation of controllable directionality. Different surface terminations are discussed and analysed. The structures provide well defined beams with enhanced spectral and spatial isolation and can serve as frequency splitters. The designs comply with the currently used materials and fabrication methods concerning the treatment of dielectric periodic media for operation in the near infrared and optical regime.

## Acknowledgement

This work was supported by the European Research Council under ERC Advanced Grant No. 320081 (PHOTOMETA). Work at Ames Laboratory was partially supported by the U.S. Department of Energy (Basic Energy Sciences, Division of Materials Sciences and Engineering) under Contract No. DE-AC02-07CH11358.

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## Graphical TOC Entry

